

V1494 Aql: Eclipsing Fast Nova with an Unusual Orbital Light Curve

Taichi KATO, Ryoko ISHIOKA, Makoto UEMURA

Department of Astronomy, Kyoto University, Sakyo-ku, Kyoto 606-8502

tkato@kusastro.kyoto-u.ac.jp, ishioka@kusastro.kyoto-u.ac.jp, uemura@kusastro.kyoto-u.ac.jp

Donn R. STARKEY

AAVSO, 2507 County Road 60, Auburn, Auburn, Indiana 46706, USA

starkey73@mchsi.com

and

Tom KRAJCI

1688 Cross Bow Circle, Clovis, New Mexico 88101, USA

tkrajci@san.osd.mil

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Abstract

We present time-resolved photometry of V1494 Aql (Nova Aql 1999 No. 2) between 2001 November and 2003 June. The object is confirmed to be an eclipsing nova with a period of 0.1346138(2) d. The eclipses were present in all observed epochs. The orbital light curve shows a rather unusual profile, consisting of a bump-like feature at phase 0.6–0.7 and a dip-like feature at phase 0.2–0.4. These features were probably persistently present in all available observations between 2001 and 2003. A period analysis outside the eclipses has confirmed that these variations have a period common to the orbital period, and are unlikely interpreted as superhumps. We suspect that structure (probably in the accretion disk) fixed in the binary rotational frame is somehow responsible for this feature.

Key words: accretion, accretion disks — stars: binaries: eclipsing — stars: individual (V1494 Aquilae) — stars: novae, cataclysmic variables — stars: oscillations

1. Introduction

Classical novae outbursts are thermonuclear runaways (TNR; cf., Starrfield, Sparks 1987; Starrfield 1999; Starrfield et al. 2000) on a mass-accreting white dwarf in cataclysmic variables (CVs) [for a general review of CVs, see Warner 1995].

Some old novae were later found to be eclipsing. The classical examples include T Aur (Nova Aur 1891, orbital period (P_{orb}) = 0.204378 d, Walker 1962; Walker 1963), DQ Her (Nova Her 1934, P_{orb} = 0.193621 d, Walker 1954; Walker 1955; Walker 1956), BT Mon (Nova Mon 1939, P_{orb} = 0.333814 d, Robinson et al. 1982), V Per (Nova Per 1887, P_{orb} = 0.10712 d, Shafter, Abbott 1989), WY Sge (Nova Sge 1783, P_{orb} = 0.153635 d, Shara, Moffat 1983). V1668 Cyg (Nova Cyg 1978, P_{orb} = 0.1384 d, Kaluzny 1990 QZ Aur (Nova Aur 1964, P_{orb} = 0.357496 d, Duerbeck 1987; Szkody, Ingram 1994).

More recently, systematic searches with deep CCD imaging have succeeded in detecting more eclipsing classical novae: DO Aql (Nova Aql 1925, P_{orb} = 0.167762 d, Shafter et al. 1993), RR Cha (Nova Cha 1953, P_{orb} = 0.1401 d, Woudt, Warner 2002), BY Cir (Nova Cir 1995, P_{orb} = 0.282 d, Woudt, Warner 2003a), DD Cir (Nova Cir 1999, P_{orb} = 0.0975 d, Woudt, Warner 2003a), CP Cru (Nova Cru 1996, P_{orb} = 0.946 d, Woudt, Warner 2003a), V849 Oph (Nova Oph 1919, P_{orb} = 0.172755 d, Shafter et al. 1993), V630 Sgr (Nova Sgr 1936, P_{orb} = 0.1180 d, Woudt, Warner 2001), QU Vul (Nova Vul 1984 No. 2, P_{orb}

= 0.111765 d, Misselt et al. 1995; Shafter et al. 1995).

Although these objects have provided a wealth of knowledge in secular (Pringle 1975; Beuermann, Pakull 1984) and nova-induced (Schaefer, Patterson 1983) period changes in classical novae, post-nova accretion disks (Wood et al. 1992; White et al. 1996), and CVs in general (Hellier 2000), the eclipsing nature of these object, however, was discovered long after their nova outbursts.

V838 Her (Nova Her 1991, P_{orb} = 0.297635 d) has been the only object whose eclipsing nature was recognized early during the nova outburst (Kato, Hirata 1991; Leibowitz 1993; Szkoody, Ingram 1994; Ingram et al. 1992). The detection of eclipses during nova outburst provides unique opportunity in determining the structure of the outbursting nova and accretion disk. This advantage has been recently best demonstrated in eclipsing recurrent novae: U Sco (Hachisu et al. 2000a; Hachisu et al. 2000b; Matsumoto et al. 2003; Munari et al. 1999), CI Aql (Matsumoto et al. 2001; Hachisu, Kato 2001; Hachisu et al. 2003), and IM Nor (Woudt, Warner 2003b).

V1494 Aql (=Nova Aql 1999 No. 2) is a bright classical nova ($V \sim 4.0$ at maximum) discovered by A. Pereira (Pereira et al. 1999). Fujii (1999) and Moro et al. (1999) reported early optical spectroscopy confirming the nova nature of this object. Pontefract et al. (1999) reported sub-mm detections with SCUBA. Further spectroscopy was reported by Kiss, Thomson (2000), Anupama et al. (2001) and Arkhipova et al. (2002). Kawabata et al. (2001) reported the evidence of an asymmetric out-

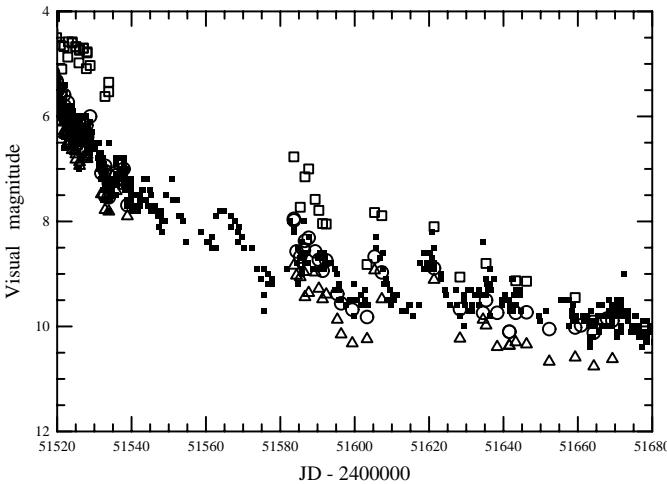


Fig. 2. Enlargement of light curve of V1494 Aql during the oscillation stage. The symbols are the same as in figure 1, supplemented with *B*-band data (open triangles).

burst from the presence of significant intrinsic polarization. Iijima, Esenoglu (2003) reported further detailed spectroscopy, which implied the presence of high-velocity jets. Drake et al. (2003) reported the discovery of X-ray pulsations with a period of 2523 s, which were ascribed to the first evidence of *g*-mode pulsations of the white dwarf in an outbursting nova.

The first suggestion of periodic short-term modulations was made by Novak et al. (2000), who reported (from observations 2000 June 7–16) 0.03 mag variations with a period of 0.0627(1) d. Retter et al. (2000) further suggested, from observations during 2000 June–August, a periodicity of 0.13467(2) d. The full amplitude of the variation grew to 0.07 mag in August. The light curve was reported to be composed of double-wave modulations. Bos et al. (2001) reported that the amplitude of the variation in 2001 June–July grew to 0.5 mag, and suggested that the light variation was caused by partial eclipse of the accretion disk. Barsukova, Goranskii (2003) refined, from observations in 2002 July and September, the period to be 0.1346141(5) d.

Figure 1 shows the light curve of V1494 Aql from observations reported to VSNET (Kato et al. 2003).¹ The three arrows represent the mean epochs of our time-resolved observations (section 2) in 2001, 2002 and 2003. The nova exhibited strong transition-phase oscillations between JD 2451530 (late 1999 December) and 2451650 (2000 April). Although early stage of this oscillation phase was presented in Kiss, Thomson (2000), we here provides a multicolor light curve covering the entire oscillation phase in figure 2. This oscillation phase is observed in a certain fraction of classical novae (Payne-Gaposchkin 1957), for which an interpretation as the intrinsic instability in a porous super-Eddington wind has been recently proposed (Shaviv 2001a; Shaviv 2001b; Shaviv 2002).

Table 1. Observers and Equipment.

Observer	Telescope*	CCD	Software
Kyoto	30-cm SCT	ST-7E	Java
Starkey	36-cm SCT	SX-10XE	AIP4Win
Krajci	28-cm SCT	ST-7E	AIP4Win

*SCT = Schmidt-Cassegrain telescope.

2. CCD Time-Resolved Observation

On six nights in 2001 November–December, one night in 2002 August, and six nights in 2003 June, we obtained CCD time-resolved photometry of this nova through the VSNET Collaboration. Compared to the optical maximum, the nova was fainter by 10, 11 and 12 mag, respectively, at the times of these observations. The observations were done with unfiltered CCD cameras. Primary and secondary local comparison stars were GSC 473.4227 and GSC 473.4367. The observed magnitudes were first reduced relative to the primary local comparison star, and were subtracted for nightly averages and slow long-term variations (less than 0.04 mag d⁻¹). The observed system was close to R_c . The errors of single measurements were typically less than 0.01–0.03 mag for Starkey and Krajci, and 0.07–0.14 mag for the Kyoto observations. The observers' details and log of observations are given in table 1 and 2, respectively. Krajci's observations were performed in Tashkent, Uzbekistan. The Kyoto observations were analyzed a JavaTM-based PSF photometry package developed by one of the authors (TK). Barycentric corrections to the observed times were applied before the following analysis.

3. Eclipses

We determined mid-eclipse times by minimizing the dispersions of eclipse light curves folded at the mid-eclipse times. The error of eclipse times were estimated using the Lafler–Kinman class of methods, as applied by Fernie (1989). As shown later, the mean eclipse light curve has a small degree of asymmetry. The error estimates should therefore be treated as a statistical measure of the observational errors (see also Kato et al. 2002 for more discussion of this application to CV eclipses).

The determined times of minima are given in table 3, as well as the minimum times from Barsukova, Goranskii (2003). The initial eclipse in Barsukova, Goranskii (2003) is defined as $E = 0$. The BJD and HJD agree within 0.0001 d at the observed epochs of Barsukova, Goranskii (2003). Although individual error estimates were not listed in Barsukova, Goranskii (2003), an overall uncertainty of 0.0002 d was given. A linear regression of the observed eclipse times (the 2001 eclipse was excluded from this regression because of the incomplete coverage of the eclipse and the rather large $O - C$ against the rest of the observations) yielded the following ephemeris (the quoted errors represent 1σ errors at $E = 1467$):

¹ (<http://www.kusastro.kyoto-u.ac.jp/vsnet/>).

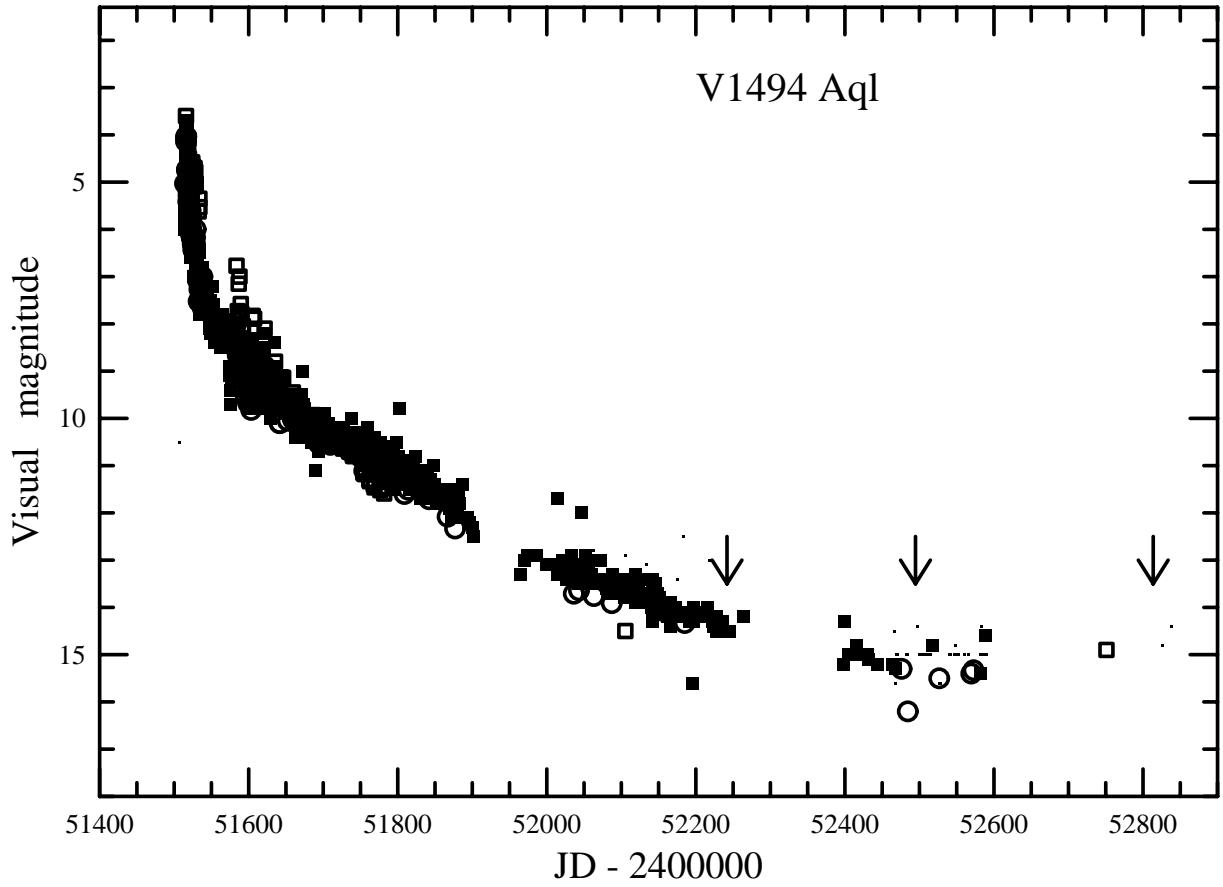


Fig. 1. Light curve of V1494 Aql from observations to VSNET. The large filled squares and small dots represent visual magnitudes and visual upper limit observations, respectively. The open circles and open squares represent CCD or photoelectric V and R_c observations. The three arrows represent the mean epochs of our time-resolved observations in 2001, 2002 and 2003.

Table 2. Journal of CCD photometry.

	Date		Start–End*	Exp(s)	N	Observer
2001	November	25	52238.919–52238.929	30	25	Kyoto
		28	52241.855–52241.946	30	218	Kyoto
		30	52243.860–52243.872	30	30	Kyoto
	December	1	52244.867–52244.879	30	28	Kyoto
		2	52245.890–52245.898	30	19	Kyoto
		4	52247.866–52247.882	30	36	Kyoto
		8	52494.651–52494.771	90	98	Starkey
2002	August	20	52810.654–52810.793	90	118	Starkey
		21	52811.668–52811.820	90	134	Starkey
		22	52812.656–52812.880	90	186	Starkey
		22	52813.322–52813.457	240	48	Krajci
		23	52813.669–52813.882	90	182	Starkey
		23	52814.262–52814.456	240	69	Krajci
2003	June	24	52815.249–52815.458	240	74	Krajci
		25	52815.684–52815.888	90	174	Starkey

*BJD–2400000.

Table 3. Eclipse minima.

BJD*	Error [†]	<i>E</i>	<i>O</i> – <i>C</i> ^{‡‡}	Source [§]
52241.8604	4	–1608	–36	1
52458.324	...	0	10	2
52458.4580	...	1	4	2
52462.4967	...	31	7	2
52464.5164	...	46	12	2
52471.513	...	98	–21	2
52473.533	...	113	–13	2
52494.6670	10	270	–17	1
52519.3042	...	453	12	2
52520.2460	...	460	7	2
52810.7410	3	2618	–9	1
52811.6840	2	2625	–2	1
52812.7617	2	2633	5	1
52813.4344	10	2638	2	1
52813.7050	2	2640	16	1
52813.8392	4	2641	11	1
52814.3756	4	2645	–9	1
52815.3184	5	2652	–4	1
52815.7217	4	2655	–10	1
52815.8573	2	2656	0	1

*BJD–2400000.

†Unit 0.0001 d.

‡Against equation (1).

§1: this work, 2: Barsukova, Goranskii (2003).

$$\text{BJD}_{\text{min}} = 2452458.3230(3) + 0.1346138(2)\text{E}. \quad (1)$$

We thus obtained a refined period of 0.1346138(2) d. We consistently use this ephemeris throughout the following discussion.

4. Orbital Light Curve

Figure 3 presents nightly averaged orbital light curves in 2003 June. Outside eclipse around phase = 0, there was a bump-like feature at phase 0.6–0.7, and a dip-like feature at phase 0.2–0.4 on almost all nights. The relative stability of the phases of these features indicate that they are unlikely features associated with superhumps (Vogt 1980; Warner 1985; Patterson 1999; see also Retter et al. 1997; Skillman et al. 1997; Olech 2002 for an example and discussion of well-observed superhumps in a fading classical nova V1974 Cyg). The same features, although the amplitudes were smaller, can be also seen in the light curves in Barsukova, Goranskii (2003), suggesting that these features have been persistently present.

Figure 4 presents a comparison of the mean orbital light curves between 2001, 2002 and 2003 [note that the mean light curve for 2001 is based on limited phase coverage (see table 2), and the mean light curve for 2002 is in fact based on a single night of data]. The overall appearance of out-of-eclipse features are common between these two epochs, confirming the tendency seen in the 2002 light curves (Barsukova, Goranskii 2003). These features were already present in 2001.

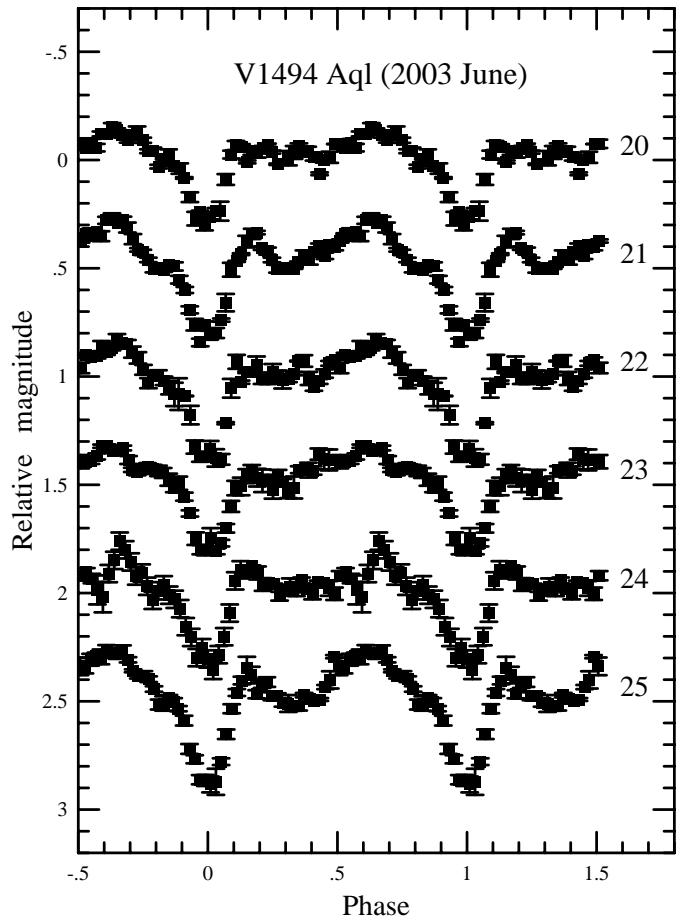


Fig. 3. Nightly averaged orbital light curves in 2003 June. The orbital phase was calculated against equation (1). The numbers in the right side represent the calendar day of June.

Figure 5 shows period analysis of V1494 Aql with the Clean method (Roberts et al. 1987), with a gain parameter of 0.01. The data were limited to $|\text{phase}| \geq 0.2$ to avoid the effect from the eclipses. The only significant periodicity is at a frequency of 7.43 d^{-1} , which is identical with the orbital period. The peak near frequencies 5.4 and 9.4 d^{-1} are side-lobes arising from the observation window. The reality of a possible weak signal around frequency 11.2 d^{-1} was not confirmed by analysis of subdivided data into 2–3 d lengths. Within 40% of the orbital period (which is a safe limit for the known superhumps: Patterson 1999), there is no indication of superhumps. The result also seems to preclude the intermediate polar-type (cf. King, Lasota 1990; Patterson 1994; Hellier 1996) magnetically controlled accretion, which was proposed to be the cause of oscillations in transition-phase novae (Retter 2002).

The double-wave orbital light curves bear resemblance to those of luminous supersoft X-ray sources (SSXS: Kahabka, van den Heuvel 1997); this phenomenological association may look reasonable in the light of supersoft X-ray detection in V1494 Aql during its post-outburst state Drake et al. (2003). The light curves of SSXS almost always show, however, brighter maximum at phase 0.2–0.4

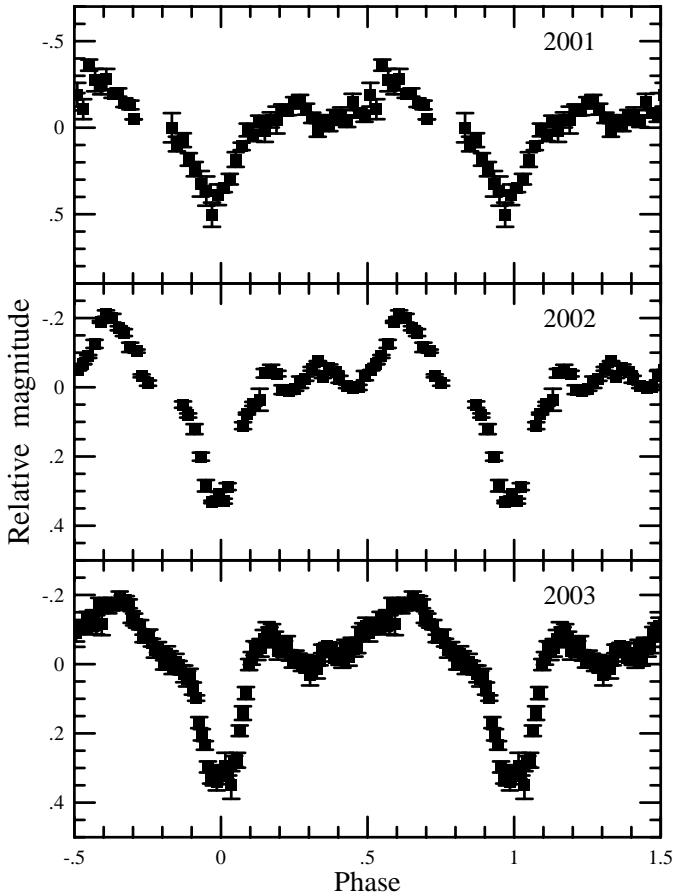


Fig. 4. Comparison of the mean orbital light curves between 2001, 2002 and 2003 (note that the 2002 light curve was constructed from a single-night observation on 2002 August 8, and that the orbital phase in the 2001 light curve was an extrapolated values; the magnitude scale is also different for the 2001 light curve). The overall appearance of out-of-eclipse features are common between these three epochs.

than phase 0.6–0.8: QR And: Beuermann et al. (1995); Matsumoto 1996; Meyer-Hofmeister et al. 1998), V Sge: Simon (1996); Simon, Mattei (1999); Steiner, Diaz (1998); Patterson et al. (1998); Simon, Mattei (2000), CAL 87: Callanan et al. (1989); Alcock et al. (1997); Hutchings et al. (1998). Model calculations (Schandl et al. 1997; Meyer-Hofmeister et al. 1997) suggest that this phenomenon can be reproduced by considering the thickening of the accretion disk rim near the stream impact point. This explanation is less likely applicable to the features observed in V1494 Aql.

Some eclipsing polars occasionally show similar light curves with similar bumps and dips: e.g. V2301 Oph (Barwig et al. 1994), MN Hya (Sekiguchi et al. 1994), HU Aqr (Schwope et al. 1993). In these polars, magnetically controlled accretion on a magnetic white dwarf synchronously rotating with orbital motion of the secondary. This possibility might be attractive because of the phase stability of the observed features. However, the quiescent magnitude of V1494 Aql more suggests a normal CV with

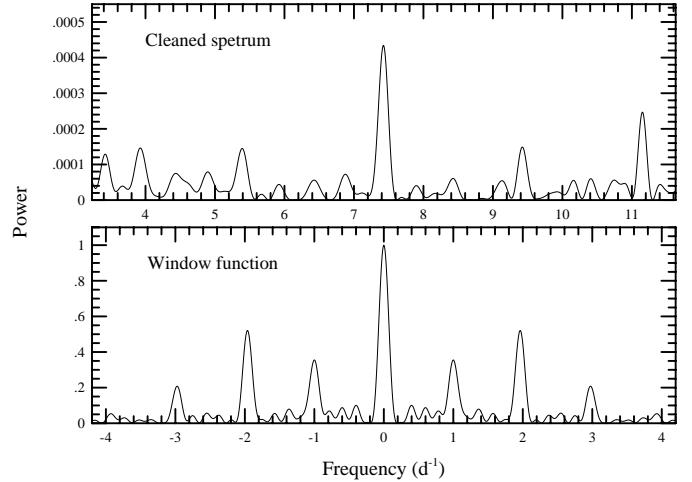


Fig. 5. (Upper:) Cleaned power spectrum outside the eclipses. The powers are given in an arbitrary unit. The only significant periodicity is at a frequency of 7.43 d^{-1} , which is identical with the orbital period. The peak near frequencies 5.4 and 9.4 d^{-1} are side-lobes arising from the observation windows. (Lower:) Window function. These diagrams are from the 2003 data.

an accretion disk (Kiss, Thomson 2000; Warner 1986), which would almost preclude the polar-type interpretation.

Among the known class of luminous (i.e. with a hot accretion disk) CVs, double-wave orbital modulations are known to be present during the early stage of superoutbursts of WZ Sge-type dwarf novae (Bailey 1979; Downes, Margon 1981; Kato et al. 2001). These modulations are called either *early superhumps* (Kato et al. 2001; Kato 2002; Ishioka et al. 2002), *early humps* (Osaki, Meyer 2002; Osaki, Meyer 2003) or *outburst orbital humps* (Patterson et al. 2002), although the last nomenclature is apparently mislabeled in that it was from the misinterpretation of the observation as an enhanced hot spot, which was originally claimed to explain the 1978 outburst of WZ Sge (Patterson et al. 1981) (see Osaki, Meyer 2003 for a discussion).

From the stability of the orbital (out-of-eclipse) light curve over years, we suspect that structure (probably in the accretion disk) fixed in the binary rotational frame, as in early superhumps of WZ Sge-type dwarf novae, is somehow responsible for the observed light curve.

5. Summary

We present long-term and time-resolved photometry of V1494 Aql (Nova Aql 1999 No. 2) based on VSNET observations. The time-resolved photometry, undertaken in 2001 November–December, 2002 August and 2003 June, confirmed that the object is an eclipsing nova with a period of $0.1346138(2)$ d. The object is a rare classical nova whose eclipsing nature was recognized during the decline stage of a nova outburst. The eclipses were equally present in all 2001, 2002 and 2003 observations. The orbital light

curve shows a rather unusual profile, consisting of a bump-like feature at phase 0.6–0.7 and a dip-like feature at phase 0.2–0.4. These features were present in almost all our observations and in those in the literature between 2001 and 2003. A period analysis outside the eclipses has confirmed that these variations have a period common to the orbital period, and are unlikely interpreted as superhumps. The double-wave modulation somewhat resembles those of supersoft X-ray sources, but the profile in V1494 Aql is different from those of supersoft X-ray source in its primary maximum occurring at phase 0.6–0.7. We suspect that structure (probably in the accretion disk) fixed in the binary rotational frame is somehow responsible for this feature.

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